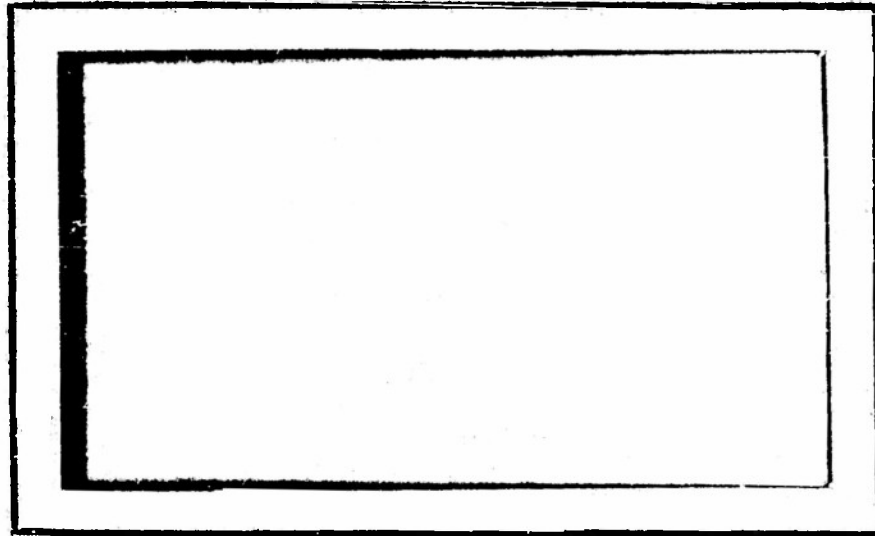


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A Preliminary Note on the Time
Scale in North Atlantic
Circulation

by

L. V. Worthington

Technical Report
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Abstract

Recent observations show that the temperature and salinity relationship of the North Atlantic Central Water Mass has changed significantly during the fifteen year period 1935-1950. This evidence, coupled with a reassessment of certain budgeting problems which arise from the exclusive use of the circulation theorem, points to a rapid turnover of water from the surface to mid-depths. It is shown that the North Atlantic Deep Water has suffered a loss of oxygen in the last twenty years; from this it is surmised that the bulk of this water was formed during the period of catastrophic cold from 1810 to 1820.

A question of great importance to the understanding of the circulation of the oceans is that of how long a period has passed since a given water type has been in contact with the atmosphere. It has long been generally accepted that the cold water which fills the deeper portions of the ocean basins has been cooled by contact with the atmosphere in high latitudes.

In the North Atlantic, Iselin (1939) has shown that a temperature-salinity curve (through the range 18° - 36.5 ‰ to 8° - 35.1 ‰) can be constructed from surface observations in late winter, along a North-South band in mid-Atlantic which differs only slightly from the temperature-salinity curve usually obtained from vertical observations, (hydrographic stations) in large areas of that ocean. This led to the concept that this water mass is formed by contact with the atmosphere and that lateral mixing and large scale sinking of surface water along σ_t surfaces are responsible for maintaining the consistent T/S relationship.

While it is by no means clear how such sinking apparently continues through the summer months there are indications, apart from the consistency of the surface and subsurface Temperature-Salinity relationship, of the existence of such a mode of circulation. There is no serious doubt, for example, that the Gulf Stream System transports a large volume of water northwards across the 45^{th} parallel, but if we are to believe solely in geostrophic circulation little of this water is returned to the south. It is possible to arrive at a rough estimate of the amount of water involved by computing the net northward volume transport between two stations, one on either side of the ocean, according to the geostrophic equation.

For purposes of this inquiry two composite stations were constructed from Wüst and Defant's (1936) subsurface atlas of temperature and salinity, one at 46°N , 45°W close to Flemish Cap and one at 48°N , 10°W on the European continental slope off

d'Ouessant. The northward volume transport (relative to the 2000 decibar surface) between these two stations was computed by means of the geostrophic equation and found to be 38 million $m^3/sec.$ If the Labrador Current carries 5 million $m^3/sec.$ southward, to the west of a line drawn between the two stations there remain 30 million $m^3/sec.,$ or thereabouts, which the geostrophic equation is unable to account for since the pressure gradients below the 2000 m level are so small as to be negligible.

Evidently this large amount of water disappears north of these stations as far as geostrophic circulation is concerned, and it is perhaps significant that roughly the same amount of water reappears in the Gulf Stream System as far as geostrophic circulation is concerned, between the Straits of Florida and Cape Hatteras. Many sources including Wüst (1924) and Parr (1937) agree that the volume transport of the Florida Current in the Straits (subject to short period variations) is about 25 million $m^3/sec.,$ and frequent sections from Montauk Point to Bermuda (Iselin, 1940) have shown that there the volume transport of the Gulf Stream is about 72 million $m^3/sec.$ If the Antilles Current adds 15 million $m^3/sec.$ to the Florida Current north of the straits there remain 32 million $m^3/sec.$ which must be added to the current by non-geostrophic means, presumably by horizontal flow along σ_t surfaces.

In attempting to assign a time scale to this movement it must be admitted that only the crudest estimates can be made on the basis of existing data. While it is contended that the water types which join the Gulf Stream in this region were once at the surface and that they submerged in high latitudes, little is known of the path by which they returned to lower latitudes. In the Florida Current region an average figure can be given of the rate of westerly flow, across a line drawn between the Little Bahama Bank and a point 100 miles off Cape Hatteras, which must take place in order to add 30 million $m^3/sec.$ to the current; this average figure is about 3 cm/sec., or 1.5 miles per day or 550 miles per year. It seems likely that this is a maximum figure for speed of flow of this type because here the width of flow is narrowest. The minimum distance from the region of surface convergence for, let us say, the 10° isotherm is 3000 miles, which at the maximum rate could be travelled in 5-1/2 years.

While this rate of turnover is almost certainly too swift, changes have recently taken place in the characteristics of the Sargasso Sea which indicate that it is not absurdly swift. In Figure 1 a comparison is shown between the Temperature-Salinity relationship in the Gulf Stream in the years 1932-1940 and in 1950. Most of the stations included fall on the Montauk Point-Bermuda section, some of the earlier (1932-1933) stations are on the Chesapeake-Bermuda section.

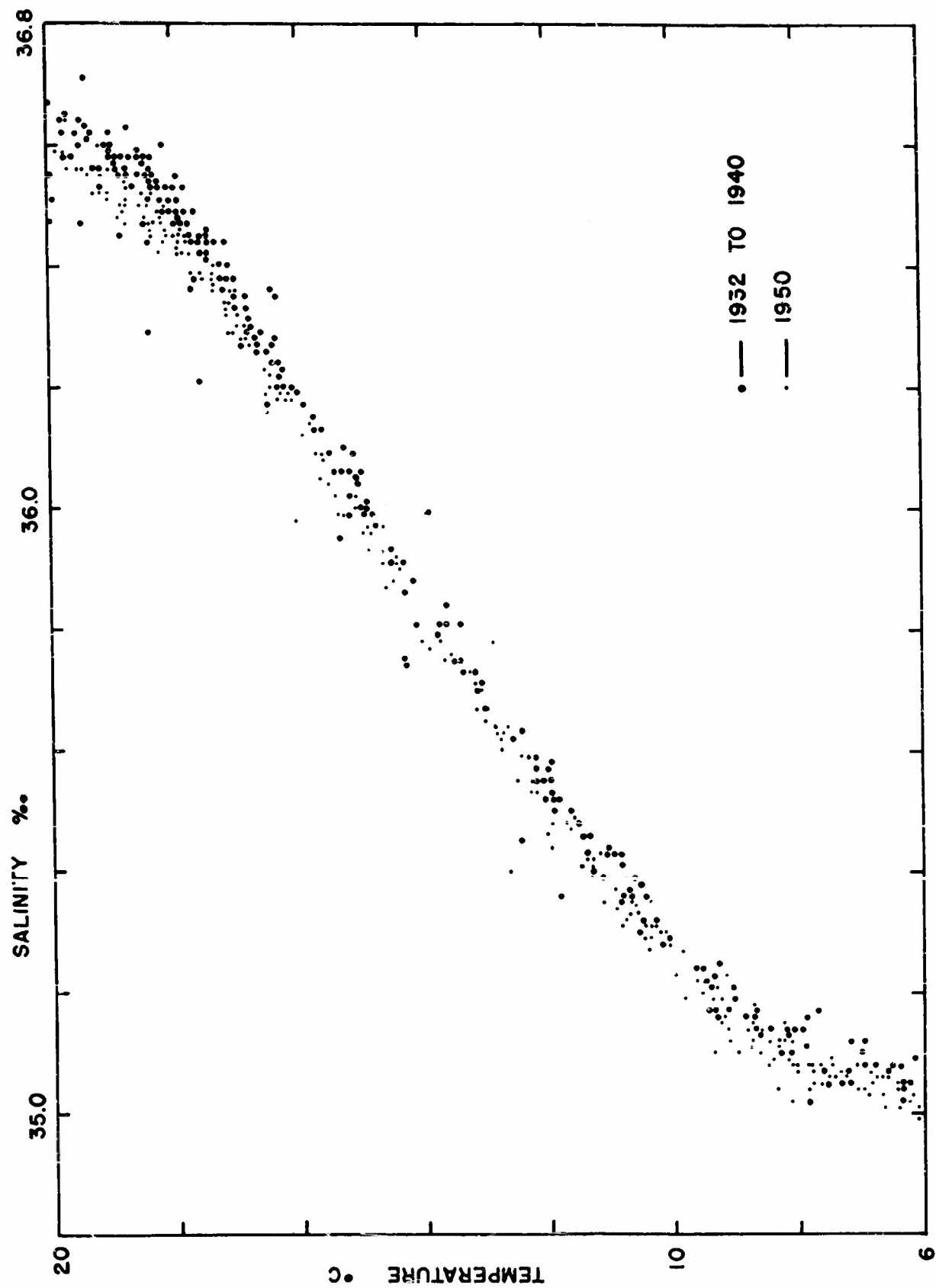


Figure 1 Comparison between the Temperature-Salinity Relationship of Gulf Stream Water in the years 1932-1940, and 1950.

In order to give a quantitative measure of the amount of this change Table I was constructed, by means of the salinity anomaly method. Iselin's (1936, Figs. 25 and 53) temperature-salinity curves for the Sargasso Sea were taken as normal. The average departure from these curves was computed for both the 1932-1940 and the 1950 Gulf Stream observations in 2°C steps, as follows:

TABLE I

Temp. Range °C.	Sal. Anom. ‰ 1932-1940	No. of Obs. 1932-1940	Sal. Anom. ‰ 1950	No. of Obs. 1950	Amount of Change (Fresher)
18 - 16	0	75	-.04	44	-.04
16 - 14	+.01	34	-.03	26	-.04
14 - 12	0	36	-.03	23	-.03
12 - 10	0	33	-.03	35	-.03
10 - 8	-.02	32	-.04	35	-.02
8 - 6	+.01	31	-.01	33	-.02
6 - 4	0	79	-.02	127	-.02
4 - 2	0	84	-.01	105	-.01

The irregularities which appear in the anomalies of both periods are thought to be real, and are ascribed to the impossibility of drawing a smooth temperature-salinity curve which is absolutely exact. The cause of this freshening (if it is indeed freshening; the same anomalies would appear if the water became about 0.2° warmer at the same salinity) is beyond the scope of this study. It is merely brought up to illustrate the fact that a change has occurred in a short time period, which argues for a brisk turnover from the surface to mid-depths, a turnover roughly consistent with the rate computed above from transport figures. That the anomalies diminish to barely significant proportions in the deep (4° to 2°) water can be taken to mean that the apparent freshening cannot be charged to differences in the technique of analysis or in the Standard Water.

In the North Atlantic Deep Water there is evidence in the form of oxygen measurements which points to a more recent turnover than is generally supposed to have occurred. Seiwel (1934) presented contours of the dissolved oxygen content of the western North Atlantic at various levels. His deepest chart (2500 m) of the distribution of dissolved oxygen in ml./l.

is reproduced here as Figure 2. It is based principally on "Atlantis" cruises from 1931-1933 and the "Dana" cruise of 1921-1922.

For comparison is offered Figure 3, based on "Atlantis" cruises from 1947 to 1954, which shows an average over-all drop in dissolved oxygen at the same level of about 0.3 ml./l. In individual stations taken during both these periods there is little change in the oxygen content of the water column vertically between 2000 m and 4500 m, which cannot be ascribed to the inaccuracies in the method of determination. Below 4500 m water of South Atlantic origin begins to be found. In Figure 4 are plotted four oxygen curves from stations north of the Greater Antilles, two from 1954, one from 1932, and one from 1922, which illustrate the loss of oxygen in that area.

Old and new data on the eastern side of the mid-Atlantic Ridge are not so plentiful, but they show that the deep water there has suffered a loss of oxygen comparable to that on the western side. In Figure 5 are plotted the values of O_2 in ml./l. at the 2000 m level from the "Armauer Hansen" cruise of 1914 (Gaarder, 1927) and "Atlantis" stations made in the years 1947 and 1948. Unfortunately the "Armauer Hansen" data do not extend to depths greater than 2000 m and so often fall in the gradient between the oxygen minimum layer and the oxygen-rich deep water. However, the comparison serves to show that the oxygen attrition is not confined to the western basin.

The "Atlantis" Mediterranean cruise of 1947-1948 is of particular interest to this study because during this cruise deep oxygen data were obtained in both the eastern and the western basins of the North Atlantic and in the Mediterranean itself. In both the Atlantic basins considerably lower values of oxygen content were found in the deep water than in previous years, while in the Mediterranean Pollak (1951) was able to contour deep oxygen values from "Dana" (1928-1930), "Thor" (1908 and 1910) and "Atlantis" (1948) observations, as if synoptically. The oxygen titrations were performed in the same manner throughout this cruise. These data infer that the loss of oxygen in the North Atlantic Deep Water is real, and cannot be attributed to differences in the technique of analysis.

It appears from a comparison of Figures 2 and 3 that in the western basin the loss of oxygen in the deep water has been roughly 0.3 ml./l. in twenty years, or 0.015 ml./l. per year. By assuming that this attrition has been going on at a steady rate it is possible to estimate by extrapolation the date at which this water was saturated with oxygen, presumably at the time that it was formed by atmospheric cooling. The date arrived at by this means is 1810.

The following sentences are quoted in this connection from Willet (1951): "At about 1800 there occurred a sharp reaction

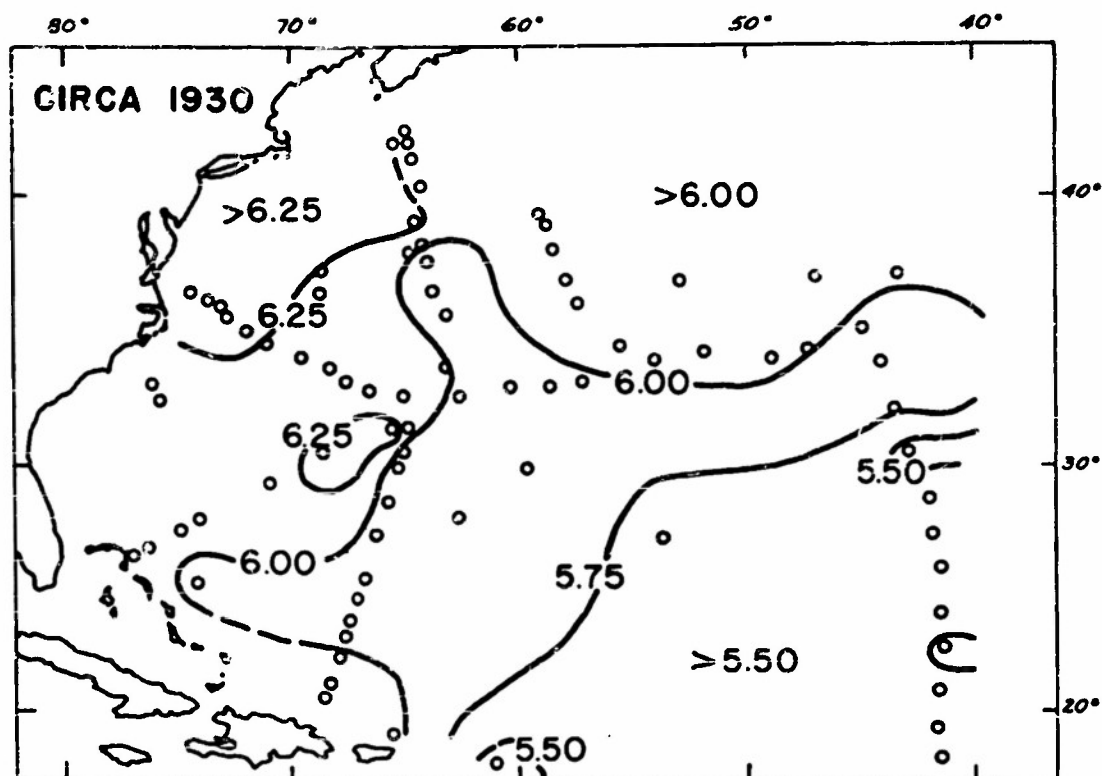


Figure 2 Distribution of dissolved oxygen, ml./l., at the 2500 m level, from Seiwel (1934).

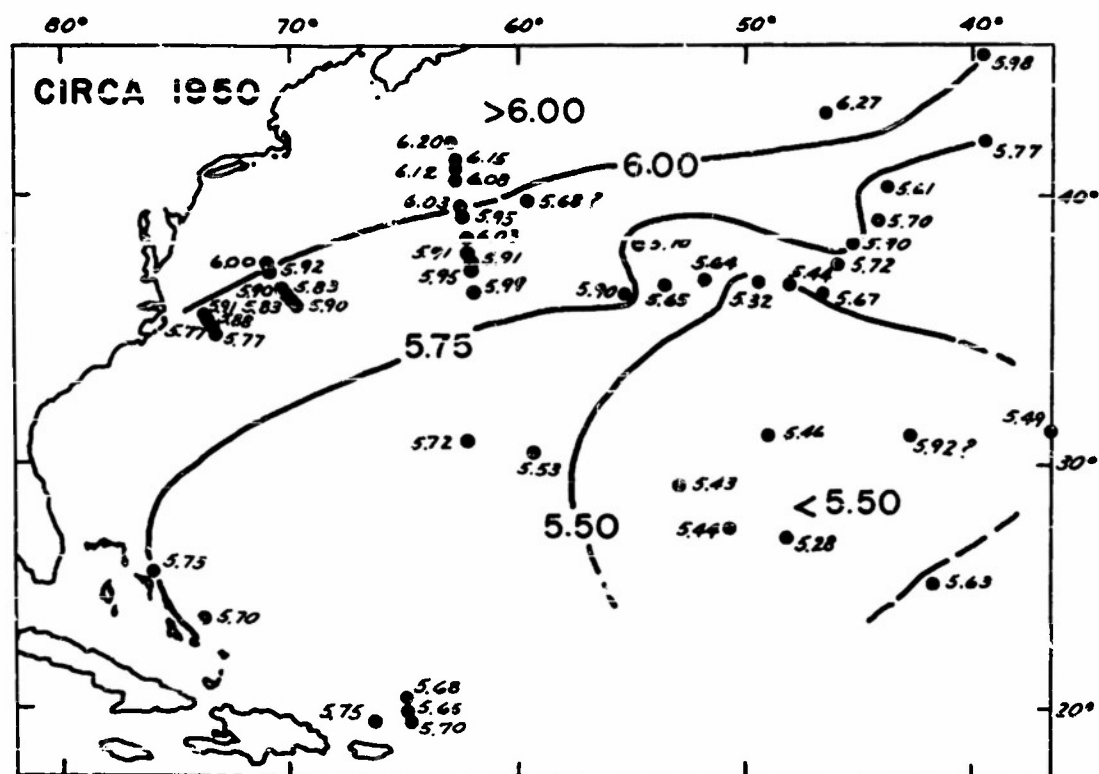


Figure 3 Distribution of dissolved oxygen, ml./l., at the 2500 m level, from "Atlantis" stations, 1947-1954.

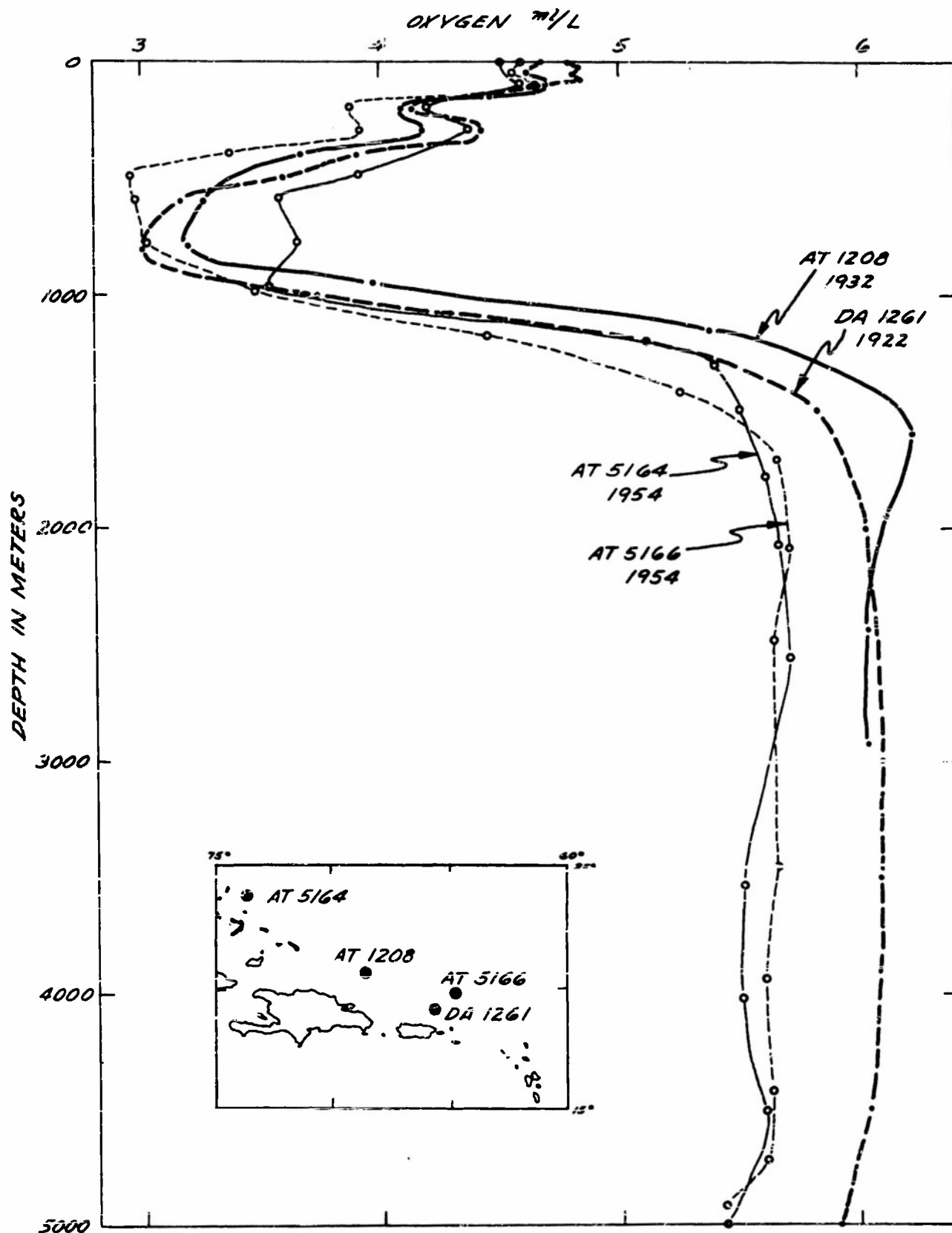


Figure 4 Vertical oxygen curves illustrating the loss of oxygen in the North Atlantic Deep Water in the area north of the Greater Antilles.

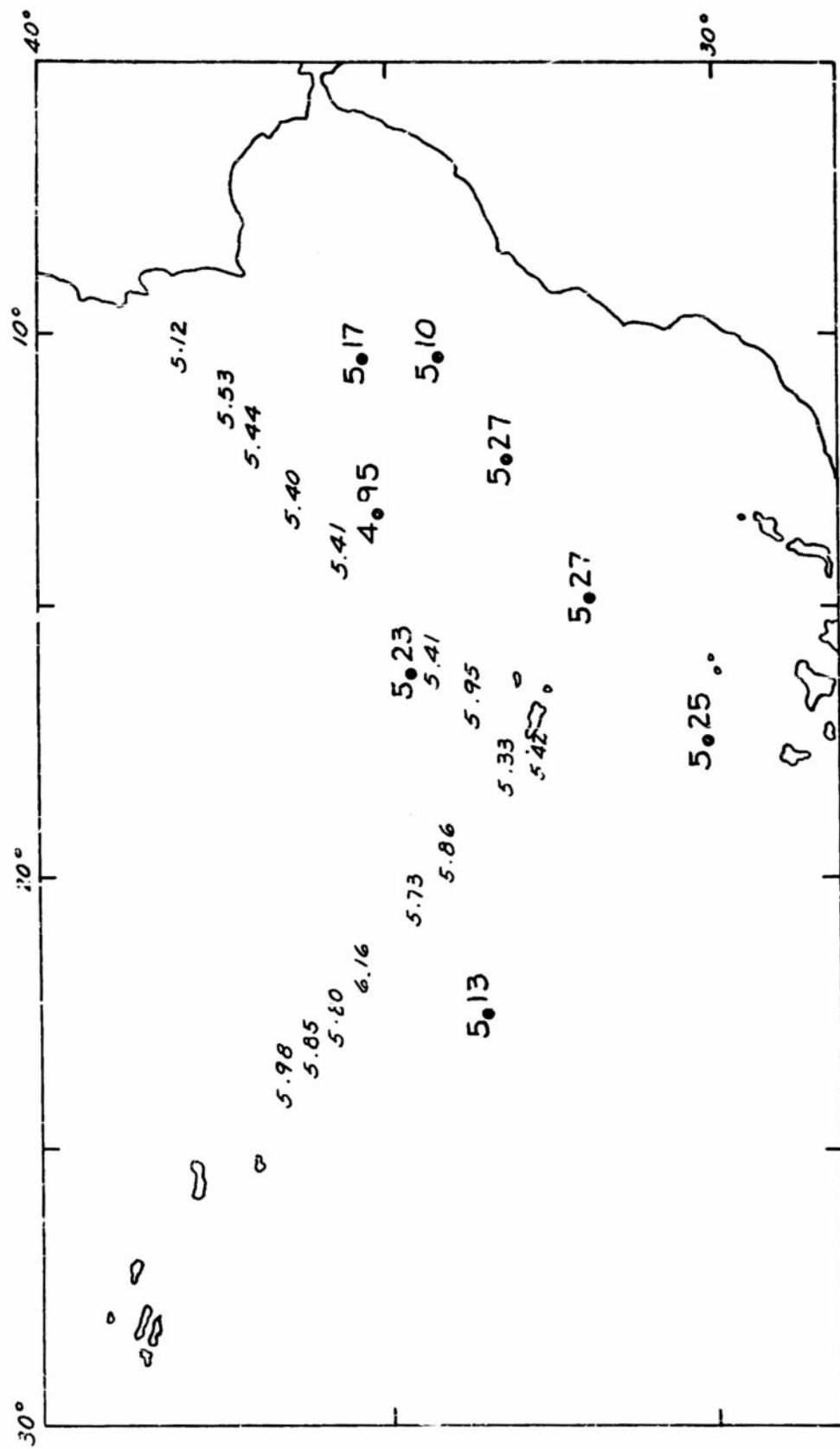


Figure 5 Dissolved oxygen values, ml./l., at the 2000 m level. Small figures are from the "Armauer Hansen" cruise of 1914 (Gaarder, 1927), the large figures are from "Atlantis" stations made in 1947-1948.

to lower temperatures which produced the severest cold on record in northern Europe, and coldness only slightly less severe in the northeastern United States. The famous 'year without a summer', 1816, occurred during this period ...". There exists a strong possibility that the bulk of North Atlantic Deep Water was produced during this catastrophe and that cooling in high latitudes in more recent years has not been sufficiently severe to produce enough water of high density to replace it.

These data are hard to reconcile with the age determinations made on sea water by Kulp (1953) by means of radiocarbon 14. Kulp's table of ocean water age measurements is reproduced here.

TABLE II

Location	Depth ft.	(Depth m)	Apparent age, yrs.
13°35'N, 66°35'W	surface	surface	recent
19°24'N, 78°33'W	surface	surface	recent
41°00'N, 54°35'W	surface	surface	recent
38°42'N, 67°54'W	13,500	4115	450 ± 150
63°46'N, 00°26'W	10,440	3182	500 ± 200
34°56'N, 68°14'W	16,560	5047	1,550 ± 300
35°46'N, 69°05'W	15,300	4663	1,950 ± 200
58°19'N, 32°57'W	6,000	1829	1,600 ± 130
53°53'N, 21°06'W	9,100	2771	1,900 ± 150

However, it appears from the positions and depths of Kulp's measurements that all the subsurface samples in Table II were taken on or close to the bottom where conceivably some exchange of carbon between the sea water and the older bottom sediments or limestone rocks might have taken place. Age determinations of water from mid-depths should prove most interesting in this connection.

In summary, if the layer in contact with the ocean bottom can be put aside for the time being, we can consider (with some oversimplification) that there are two types of turnover which take place in the North Atlantic. The first, which is taking place continually, consists in water being transported to high latitudes by geostrophic currents and returned to lower latitudes by sinking along σ_t surfaces. In this type of circulation no violence is done to the water's identity as a water

mass, and its temperature and salinity relationship remains essentially unchanged. Such changes as do occur are probably the result of the ocean's rapid response to climatic changes, and should take a prominent part in the study of these changes.

In the second, a vast amount of water of a single or nearly single water type is formed in successive years of catastrophic cold at high latitudes. To perform this, many water types must be combined into one by large scale top to bottom mixing. The North Atlantic Deep Water which was seemingly formed in this manner has penetrated as far as 40° south and comprises about half of the entire contents of the North and South Atlantic Oceans. How much of this water was formed in the individual catastrophe of 1810-1820 is open to question, as is the possibility of tracing different portions of this water to climatic changes in the more recent or remote past. Such questions cannot be answered without repeated re-examinations of the oceans.

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